EXHIBIT I

PHY+MAC Channel Sounding Interval Analysis for IEEE 802.11ac MU-MIMO

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Abstract—**The emerging IEEE 802.11ac standard introduces spatial division multiplexing access, in its downlink version, to the wireless local access world. Through this multi-user multiple input multiple output (MU-MIMO) technique the access point (AP) can simultaneously transmit multiple independent groups of streams to different stations. The consequent precoding requires precise channel knowledge and thus regular channel sounding and feedback. The interval to choose for this sounding procedure is an important factor. A compromise between precise channel knowledge at the AP and reduction of the associated overhead is needed. The first is a physical (PHY) layer parameter and the second is evaluated at the medium access control (MAC) layer. In this paper we present a PHY+MAC analysis of the impact of the channel sounding interval on MU-MIMO transmissions for different scenarios.**

Keywords: channel sounding; cross-layer simulator; crosstalk interference; IEEE 802.11ac; MU-MIMO; sounding interval

I. INTRODUCTION

IEEE 802.11ac standard is the emerging IEEE wireless local access network (WLAN) standard for below 6 GHz transmissions [1]. By incorporating a multi-user (MU) dimension to the classical multiple input multiple output (MIMO) configuration, it enables medium access control (MAC) throughputs of up to 1 Gbps [2]. Indeed the access point (AP) can simultaneously transmit independent streams to multiple stations by applying crosstalk interference (CTI) minimizing precoding vectors. However, the AP has to have precise knowledge of the channels of all the stations which are to be served by MU-MIMO transmissions. To that end, a channel sounding procedure is regularly engaged so that the concerned stations can feed back their respective channel estimates. The frequency of this sounding procedure, and thus the aging of the obtained estimates, has an important impact on performance. However, there is no indication on which interval to take in the standard.

In this paper, we present the impact that the channel sounding interval can have on throughput. To do so, we use an IEEE 802.11ac multiple-user simulation platform containing an all inclusive physical (PHY) layer combined with an elaborated MAC layer and working in a symbiotic manner [3]. The aging of channel estimates is therefore precisely accounted for while finely simulating contention mechanisms. A similar study has been done in [4]. This interesting work was written during the first phases of the IEEE 802.11ac standardization process, thus not being compliant to the current version of the standard. In addition, the resulting analysis was done firstly from a PHY perspective then from a MAC perspective. In the present paper however, we present a combined PHY+MAC analysis using 802.11ac compliant chains, thus leading to realistic recommendations.

The rest of this paper is organized as follows. Section II presents an overview of main 802.11ac PHY and MAC features. Section III focuses on one of these features which is the channel sounding and feedback procedure. This is followed in Section IV by a short description of the PHY+MAC simulation platform. Simulation parameters and statistical results are then given in Section V. This naturally leads to the simulation results which are presented and discussed in Section VI. Section VII concludes this paper.

II. MAIN IEEE 802.11AC FEATURES

A. *PHY layer features*

1) *Unchanged IEEE 802.11n features*

Most of the mandatory features of the IEEE 802.11n standard [5] have been incorporated in the IEEE 802.11ac standard [1]. This includes the use of constellation sizes of up to 64 QAM and two bandwidths (20 MHz and 40 MHz). MIMO, which is one of the main PHY add-ons of 802.11n, is of course still used. The use of MIMO enables the simultaneous transmission of up to four spatial streams towards a particular station.

2) *New features*

a) *Increase in constellation size and spatial stream number*

The IEEE 802.11ac standard has been defined to enable multi-gigabit transmissions in the 5 GHz band [6]. One natural means of increasing data rates is to increase the maximum constellation size. 256 QAM is thus defined. However, the gains are not sufficient to meet the set objectives. A sure means of multiplying attainable data rates is to increase the maximum number of spatial streams to eight. This implies however increasing the number of parallel coding chains and also the number of front-end chains. This solution is rather costly [2].

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b) Further channelization

A lower cost alternative for important gains is the enlarging of the used bandwidth. The leap from 20 MHz to 40 MHz is extended to 80 MHz and even 160 MHz so as to virtually double and quadruple (resp.) the possible data rates.

c) MU-MIMO

Just as MIMO was the new technique of 802.11n, MU-MIMO is that of 802.11ac. An AP can simultaneously transmit independent groups of streams to multiple stations. It can thus make use of one channel access to transmit “unicast” data to a group of stations. Up to four independent groups of streams can be transmitted. The antennas available at the AP can therefore be used to increase system efficiency. There is no explicit indication on which precoding technique to use for MU-MIMO transmissions in 802.11ac. However CTI between the served stations should be minimized. We have chosen the block diagonalization precoding technique [7] because of the good performance-complexity tradeoff it offers. This scheme tries to cancel CTI through zero forcing. It simplifies to channel inversion precoding for single antenna stations.

B. MAC layer features

1) Unchanged IEEE 802.11n features

The consequent increase in PHY data rates enabled by 802.11n, relative to previous standards, implied greater MAC packet data unit sizes, lest the efficiency be greatly reduced. MAC aggregation is the solution. In 802.11ac, both aggregate MAC service data units and aggregate MAC packet data units are used, though with increased maximum sizes, and can even be concatenated for greater efficiency [2].

2) New features

Using MU-MIMO implies precoding the streams to send for each station, and thus, having precise knowledge of their channels. This is done through explicit channel feedback. Special frames, which are overhead with regards to data, are exchanged so as to regularly feed back the channel state information to the AP. Another implication is that groups of stations are to be defined by the AP. It is based on the resulting identifier that stations will retrieve their data from received MU-MIMO frames. Finally, the acknowledgment procedure is also adapted to enable destination stations to acknowledge their received frames.

III. Channel Sounding and Feedback in IEEE 802.11ac

Let us take a closer look at the channel sounding and feedback protocol in 802.11ac. In the previous 802.11n standard, the multiplicity of options for the sounding protocol has made things difficult for interoperability when using beamforming (BF) techniques [6]. Consequently, 802.11ac uses a unique protocol based on the use of a null data packet (NDP) for channel sounding and compressed beamforming matrices for feedback.

1) Protocol

As illustrated in Fig. 1, the AP announces the beginning of a sounding procedure through a NDP announcement (NDPA) frame [1]. In it the AP advertizes the beamformees' addresses (through a group identifier) and specifies the address of the first responding beamformee. The concerned stations can thus prepare themselves to receive the upcoming NDP frame, and consequently compute their respective beamforming matrices. The frame exchange is punctuated with short inter-frame sequences (SIFS). Upon reception of the NDP, the first responding station replies immediately after with the compressed version of its BF matrix. The AP then polls the remaining stations for their respective BF matrices. For practical reasons, the maximum number of beamformees per group is limited to four [6]. The reader shall note that for single-user (SU) beamforming, the protocol ends after the first feedback frame. In addition, stations can send sounding frames to the AP, but for single user beamforming ends.

2) Parameters

The duration of the channel sounding procedure depends on the parameters given in Table I. Clearly the main parameters are the number of beamformees and the number of spatial streams. Another overhead adding parameter is the channel sounding interval. As explicated in [6], MU-MIMO is much more sensitive to feedback errors and aging than classical single user MIMO (SU-MIMO) beamforming. This implies that channel sounding has to be done more frequently than for SU-MIMO. There is no indication on which interval to take in the standard but studies show that it will be smaller than SU-MIMO's 100 ms [4].

IV. 802.11ac PHY+MAC Simulation Tool

We propose to use the new multi-user simulation platform presented in [3]. It is composed of an all inclusive 802.11ac PHY layer and an elaborated 802.11ac MAC layer working in a symbiotic manner. Both the PHY layer, containing a realistic channel model, and the MAC layer are finely represented. An accurate modeling of reality is thus made possible.

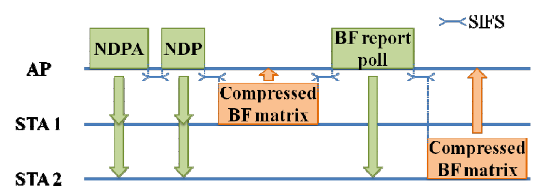


Fig. 1. IEEE 802.11ac channel sounding procedure for two stations

TABLE I. IEEE 802.11ac sounding and feedback parameters

Frames / Fields		**Conditioning parameters**
NDP		Beamformer's number of antennas
Compressed BF matrix	Signal to noise ratio information	Number of spatial streams
	Channel matrix element	Bandwidth
		Subcarrier grouping
		Beamformee's number of spatial streams
		Beamformee's number of antennas
		Number of angle quantization bits (Ψ and Φ)
	MU only information	Bandwidth
		Subcarrier grouping
		Beamformee's number of spatial streams

A. *Fine grained 802.11ac PHY section*

The PHY section of the simulator is compliant with the IEEE 802.11ac PHY specifications [1]. In order to faithfully account for WLAN channel variations through time, the very high throughput task group (TGac) [8] channel model is also used. This way, the aging of channel tap estimates and the effect of CTI on MU-MIMO transmissions can be faithfully accounted for [9]. Thus, compared to a MAC-centric approach, which oversimplifies the PHY layer, our PHY+MAC simulator structure allows a more reliable PHY section.

B. *Elaborated 802.11ac MAC section*

The MAC section of the simulator is compliant with the IEEE 802.11ac MAC specifications [1]. We have used the adaptive multi rate retry algorithm (AMRR) [10]. This rate adaptation algorithm has long-term and short-term adaptation mechanisms for reducing latency while increasing throughput. Thus, traffic generation, queueing, and channel access, as well as acknowledgment, are all taken into account in our PHY+MAC simulator. It would not have been the case in a PHY-centric approach where all of the previous MAC and upper layer functions are simplified.

C. *Symbiotic sections*

The two sections work in a symbiotic manner. The MAC section first determines the transmitting and receiving stations. It then hands over information on the frame to be transmitted to the PHY section. The latter adapts to the transmission context (i.e. transmitter, channel, and receiver). The PHY section then forms the PHY protocol data unit, transmits it through the TGac channel, and decodes the received information. The decoded bits, which will be checked through the included forward check sum, are returned to the MAC section.

V. SIMULATION SCENARIOS AND PARAMETERS

A. *Studied scenarios*

In this paper the impact that the channel sounding interval may have on MU-MIMO is evaluated. To this end, the three scenarios presented in Table II are studied. Through these scenarios, we can evaluate how the system reacts to an increase in the number of stations and to an increase in the number of antennas.

B. *Simulation parameters*

The TGac channel, 802.11ac PHY, and 802.11ac MAC simulation parameters common to all three scenarios are given in Table III, as defined in the IEEE 802.11ac standard [1].

C. *Statistical saturation throughput results*

By taking average channel access durations, the maximum average saturation throughput can be obtained. The statistically obtained results are given in Table IV. We can see that, for MU-MIMO, the more frequent the channel sounding, the lower the obtained throughput. This is natural considering the implicated overhead. The difference is less important for SU-MIMO. When comparing scenarios 1 and 3, which both have 2 stations, it might seem surprising at first sight that scenario 3 would offer lower throughput than scenario 1 despite the increase in antenna diversity. However, these throughput results being statistical, the benefits of spatial diversity cannot be accounted for but only the increase in overhead (PHY preamble, mainly, and sounding).

TABLE II. PER SCENARIO SIMULATION PARAMETERS

Scenario	Number of stations	Number of antennas: At AP	Number of antennas: At each station
1	2 stations	3	1
2	3 stations	3	1
3	2 stations	4	2

TABLE III. COMMON SIMULATION PARAMETERS

Global simulation parameters		
Application rate		80 Mbps
Application duration		2 seconds
Transport layer protocol		User datagram protocol (UDP)
AP-station distance		5 meters
MAC layer parameters		
Access category		Best effort
MAC service data unit size		1500 octets (typical payload format)
Max. allowed transmit opportunity (TxOP) [a]		3.008 ms
Max. aggregation size [b]		17 for MU and 18 for SU
Queue management		One access category queue per station [c].
Rate adaptation algorithm: AMRR	Initial rates	$r_0=r_1=r_2=r_3=6.5$ Mbps
	Counts	$c_0=3$, $c_1=3$, $c_2=1$, $c_3=3$
Activated modulation and coding schemes		0 to 8 for 1 spatial stream
Sounding and feedback: Compressed feedback	Interval	10/20/30/40 ms for MU, 100/140 ms for SU
	Grouping	None
	Ψ angle quantization	2 bits for SU, 5 bits for MU
	Φ angle quantization	4 bits for SU, 7 bits for MU
PHY layer parameters		
Number of spatial streams		1
Transmit power		17 dBm
Antenna gain		None
Received additive white Gaussian noise (AWGN) level		7 dB
System loss		8.5 dB
Channel coding		Binary convolutional coding
Guard interval		Long
Channel estimation		Done once at the beginning of the received frame. Affected by AWGN.
TGac channel parameters		
Channel model		B (residential)
Bandwidth		20 MHz
Central carrier frequency		5.2 GHz (channel n°40)
Channel seed		19
Client identification index		1, 2 (and 3) for station 1, 2 (and 3) resp. [d]

a. To limit an end-usage-wise realistic transmission duration

b. Because of imposed TxOP limitation and number of spatial streams

c. To prevent starvation in MU-MIMO

d. TGac recommendations

TABLE IV. STATISTICALLY OBTAINED SATURATION THROUGHPUT

Used scheme	Sounding interval (ms)	Total saturation throughput (Mbps)		
		Scenario 1	Scenario 2	Scenario 3
MU-MIMO	10	130.25	183.74	127.56
	20	133.70	190.85	132.35
	30	135.07	193.69	134.27
	40	135.76	195.12	135.23
SU-MIMO	100	71.17	70.38	71.09
	140	71.35	71.17	71.32

VI. SIMULATION RESULTS

The results in Table IV give the maximum attainable average throughputs. Realistic throughput results, i.e. jointly accounting for PHY and MAC parameters, are given in this section.

A. Scenario 1: triple antenna AP and 2 single antenna stations

The total downlink throughputs for scenario 1 using MU-MIMO and SU-MIMO with different channel sounding intervals are given over time in Fig. 2 (a). Although the throughputs for SU-MIMO roughly correspond to the tabulated values, those of MU-MIMO are quite different. The throughput gap between MU-MIMO with 10 ms and 40 ms channel sounding interval is not only inversed but almost multiplied by 10.

The stability of the SU-MIMO curves can be partly explained by the multi-user diversity effect. The AP can take advantage of the difference in channel states. When using MU-MIMO, the AP transmits to both stations as long as there is data available for each, because they belong to the same group. Considering that saturated throughputs are evaluated here, the AP transmits to both stations every channel access, thus benefiting less from this diversity. The other, and main reason why SU-MIMO throughputs are so stable is that, considering that stations are only 5 meters away from the AP, channel conditions are good. However, for MU-MIMO, the correlation between these channels becomes an important factor. The TGac channel 19 used here is a channel with important correlation, thus leading to quite poor performance [9].

The solid-line and cross-marker curves in Fig. 2 (b) give the received signal powers' evolution over time for MU-MIMO and SU-MIMO (resp.) for both stations. The displayed power levels are normalized over the noise-free and deep fade-free received signal power. Firstly, the reader can notice that the use of channel inversion reduces the received signal strength. Indeed, in channel inversion precoding, precoding vectors have to be chosen in the null space of other stations' channel matrices [7], lowering the odds of choosing the power maximizing vector. The received interference levels for MU-MIMO (circular markers) are also given in Fig. 2 (b) for both stations. These interference levels are determined using the long training fields that are precoded with the other station's BF vector and are normalized over useful signal power.

By corresponding Fig. 2 (a) and Fig. 2 (b), it can be seen that the received power level has a direct influence on throughput. Indeed, the estimation errors have greater impact when the signal powers are low. During these low power phases (e.g. between 0.6 s and 0.8 s or between 1.6 s and 2 s), the CTI levels rise considerably. This leads the rate adaptation algorithm to decrease the PHY data rate. Thus, channel estimates have to be refreshed more frequently during these phases to minimize the impact that estimation errors and aging can have on performance. This way, important gains can be observed despite an increase in overhead. In this particular scenario however using a static 10 ms sounding interval can enable important gains.

B. Scenario 2: triple antenna AP and 3 single antenna stations

The AP having three antennas and stations supporting only one spatial stream, the former can support MU-MIMO transmissions towards a group of three such stations. Consequently, the case where a station is added is considered in scenario 2. Fig. 3 (a) illustrates the total downlink throughputs for this scenario. The analysis done in scenario 1 is still valid here. However the impact on performance is much worse in scenario 2. Contrary to the statistical results where a 40% increase in throughput is expected when moving to scenario 2, a 60% decrease can be observed. This is mainly due to two phenomena. The first is that the 802.11 standard family limits the maximum energy that a station can transmit. Accordingly, the AP has to satisfy this constraint when engaging MU-MIMO transmissions.

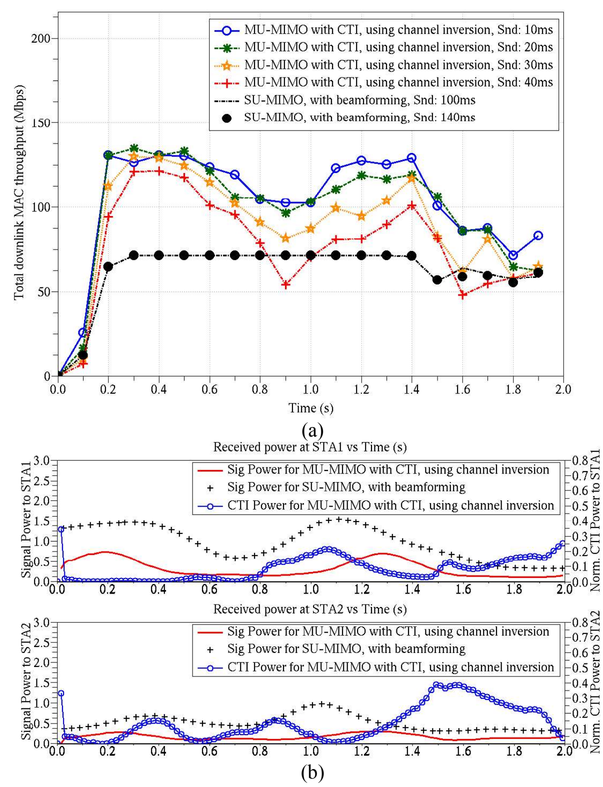
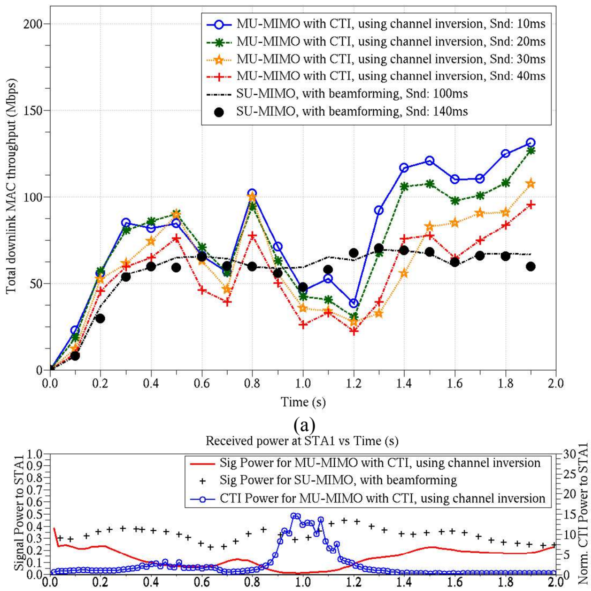


Fig. 2. Scenario 1:
a) Total downlink MAC throughput;
b) Received useful signal power and normalized crosstalk interference power for both stations (STA1 and STA2)



(a)

(b)

Fig. 3. Scenario 2:
a) Total downlink MAC throughput;
b) Received useful signal power and normalized crosstalk interference power for station 1 (STA1)

Therefore there is less available energy per station in scenario 2 than in scenario 1, leading to the use of more robust PHY data rates. The second reason is that the AP has no longer the degree of freedom in the null space search it had in the previous scenario. Having three independent streams to transmit on three antennas complicates things for channel inversion precoding. The obtained precoding vectors are quite low. This can be seen in Fig. 3 (b) through the useful signal power received by station 1. The interference power levels can thus be very high, with regards to those of scenario 1. Therefore it is again preferable to sound the channels more frequently. A static 10 ms interval is well suited for this particular scenario with correlated downlink channels.

C. *Scenario 3: quadruple antenna AP and 2 double antenna stations*

In scenario 3 the effect of increasing antennas, both at AP and stations, is studied. Fig 4 illustrates the total downlink throughputs towards the two available stations. The reader shall note that the number of spatial streams is still set to 1. The stations can thus make profit of spatial diversity to improve their respective receptions. This explains the overall good performance. In addition, there is little throughput difference between sounding intervals. The AP could therefore dynamically dimension the channel sounding interval based on the fed back received signal to noise ratio. Performance can thus be maintained while reducing channel occupation to accommodate for other transmissions. A simpler solution in this scenario would be to choose a 40 ms sounding interval.

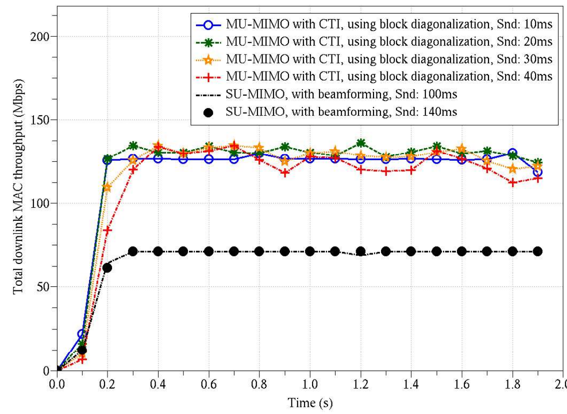


Fig. 4. Scenario 3: Total downlink MAC throughput

VII. CONCLUSION

In this paper, MU-MIMO channel sounding interval is analyzed from a PHY and MAC layer perspective. The joint PHY-MAC analysis of the three scenarios using quite correlated channels showed that frequent sounding can lead to an increase in throughput despite the associated overhead. A dynamic dimensioning of the interval based on the current channel states can be considered either to increase throughput or reduce overhead. We plan to implement such a mechanism, and particularly study its impact in a loaded environment.

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